Hard and soft probe - medium interactions in a 3D hydro+micro approach at RHIC

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Abstract. We utilize a 3D hybrid hydro+micro model for a comprehensive and consistent description of soft and hard particle production in ultra-relativistic heavy-ion collisions at RHIC. In the soft sector we focus on the dynamics of (multi-)strange baryons, where a clear strangeness dependence of their collision rates and freeze-out is observed. In the hard sector we study the radiative energy loss of hard partons in a soft medium in the multiple soft scattering approximation. While the nuclear suppression factor R_{AA} does not reflect the high quality of the medium description (except in a reduced systematic uncertainty in extracting the quenching power of the medium), the hydrodynamical model also allows to study different centralities and in particular the angular variation of R_{AA} with respect to the reaction plane, allowing for a controlled variation of the in-medium path-length.

Experiments at the Relativistic Heavy Ion Collider (RHIC) have established a significant suppression of high-p_T hadrons produced in central A+A collisions compared to those produced in peripheral A+A or binary scaled p+p reactions, indicating a strong nuclear medium effect [1, 2], commonly referred to as *jet-quenching*. Within the framework of perturbative QCD, the leading process of energy loss of a fast parton is gluon radiation induced by multiple soft collisions of the leading parton or the radiated gluon with color charges in the quasi-thermal medium [3, 4, 5].

Over the past two years, a large amount of jet-quenching related experimental data has become available including but not limited to the nuclear modification factor R_{AA}, the elliptic flow v_2 at high p_T (as a measure of the azimuthal anisotropy of the jet cross section) and a whole array of high p_T hadron-hadron correlations. Computations of such jet modifications have acquired a certain level of sophistication regarding the incorporation of the partonic processes involved. However, most of these calculations

have been utilizing over-simplified models for the underlying soft medium, e.g. assuming a simple density distribution and its variation with time. Even in more elaborate setups, most jet quenching calculations assume merely a one- or two-dimensional Bjorken expansion.

The availability of a three-dimensional hydrodynamic evolution code [6] and related hybrid approaches allow for a much more detailed study of jet interactions in a longitudinally and transversely expanding medium. The variation of the gluon density in these approaches is very different from that in a simple Bjorken expansion. A previous calculation in this direction [7, 8] estimated the effects of 3-D expansion on the R_{AA}. However, this approach treated the energy loss of jets in a rather simplified and heuristic manner. Here, we shall perform a detailed investigation of the modification of jets in a three dimensionally expanding medium within the BDMPS formalism utilizing quenching weights as described in [9]. In addition, 3-D hydrodynamic and hybrid models have been very successful in describing the majority of features of soft particle production at RHIC (with HBT interferometry being the sole exception) – this we shall utilize in order to determine the medium properties for the jet-quenching calculation.

In this write-up, we utilize a state-of-the-art fully 3-D hybrid hydro+micro transport model [6]. The model employs relativistic 3D-hydrodynamics for the early, dense, deconfined stage of the reaction and a microscopic non-equilibrium model for the later hadronic stage where the equilibrium assumptions are not valid anymore. It is capable of self-consistently calculating the freezeout of the hadronic system, while accounting for the collective flow on the hadronization hypersurface generated by the QGP expansion. The initial conditions of the hydrodynamic calculation are tuned to describe the hadronic data in the soft sector, such as hadron yields, spectra, rapidity-distributions as well as radial and elliptic flow. Note that while the modeling of the hadronic stage is of paramount importance for the proper description of the medium in the soft sector, it does not contribute to the jet energy loss.

In the left frame of Fig. 1 we analyze the P_T spectra of multistrange baryons. Our results show good agreement with experimental data for Λ, Ξ, Ω from the STAR collaboration [10, 11]. Recent experimental results suggest that at thermal freezeout multistrange baryons exhibit less transverse flow and a higher temperature closer to the chemical freezeout temperature compared to non- or single-strange baryons [10, 11]. This behavior can be understood in terms of the flavor dependence of the hadronic cross section, which decreases with increasing strangeness content of the hadron. The reduced cross section of multi-strange baryons leads to a decoupling from the hadronic medium at an earlier stage of the reaction, allowing them to provide information on the properties of the hadronizing QGP less distorted by hadronic final state interactions [12, 13, 14]. In microscopic calculations the early decoupling will manifest itself via a reduced number of collisions for the respective hadron species. It should be noted that the analogous behavior has already been observed in experiments at the CERN-SPS [15, 16, 17, 18, 19].

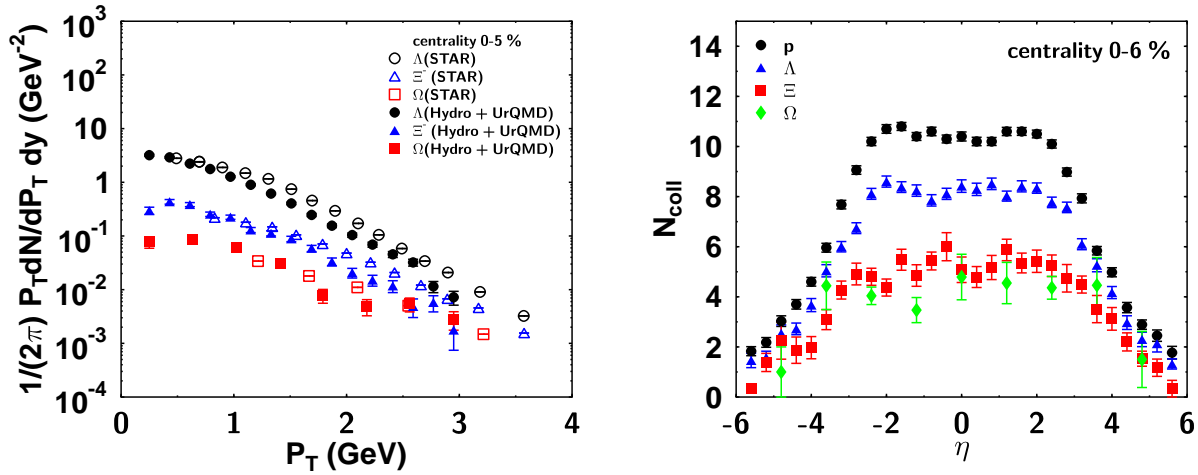The pseudo-rapidity dependence of the number of hadronic rescatterings for

Figure 1. Left: P_T spectra of (multi-)strange baryons calculated in a hybrid hydro+micro approach compared to STAR data. Right: pseudo-rapidity distribution of the number of rescatterings for baryons of varying strange quark content.

different baryon species can be used to corroborate the above findings and is analyzed in the right frame of Fig. 1, which shows the number of collisions of p, Λ, Ξ and Ω as a function of η at $b = 2.4$, 4.5 and 6.3 fm. The distributions appear to be similar to that of the particle yield psuedorapidity distribution. At midrapidity we find a plateau region extending from $\eta = -3$ to 3, followed by a steep drop-off to forward and backward rapidities. The flavor dependence of the average collision numbers is again clearly seen, even though we would like to point out that the shapes of the different distributions are very similar. The large plateau region indicates the rapidity domain in which *interacting* matter can be found and in which the application of thermodynamic concepts is viable.

Having determined the properties and dynamics of the soft sector, we can now utilize the time-evolution of the medium provided by our model for the calculation of jet energy-loss. Thus, our calculation significantly reduces the systematic uncertainties usually associated with the medium parametrization and allows for a precision calculation of all effects associated with hard probe - medium interactions. Our calculation follows the BDMPS formalism for radiative energy loss [20] using quenching weights as introduced by Salgado and Wiedemann [21, 9].

In [22, 23] it has been shown that R_{AA} for central collisions only constrains a scale, but not the detailed functional form of energy loss probability distribution $\langle P(\Delta E)\rangle_{T_{AA}}$. In the approach outlined above, this is manifest in the parameter K in the expression for the local transport coefficient $\hat{q}(\xi)$:

$$\hat{q}(\xi) = K \cdot 2 \cdot \epsilon^{3/4}(\xi) \tag{1}$$

which then was adjusted to the data in central collisions. We illustrate in the left frame of Fig. 2 that three different dynamical models, a 2D hydrodynamical evolution [24], the 3D hydrodynamical evolution outlined above [6] and a parametrized fireball
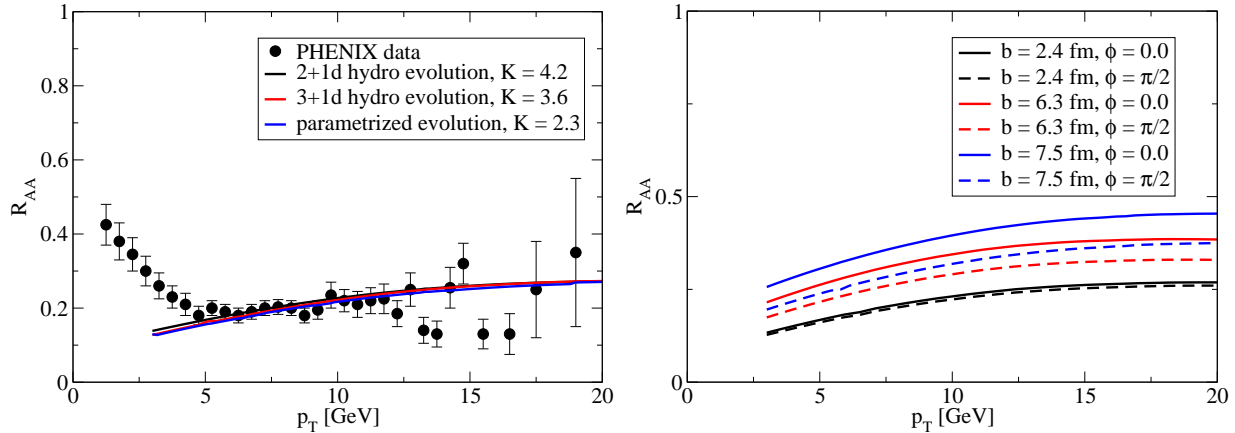
Figure 2. Left: R_{AA} for central collisions as calculated in three different models for the medium evolution with the overall quenching power scale K adjusted to data. Right: p_T dependence of R_{AA} in plane (solid) and out of plane (dashed) emission at different values of impact parameter **b**.

evolution [25] give almost equal descriptions of R_{AA} once the scale parameter is adjusted, albeit they require different values of K (the chief reason for this being the different longitudinal dynamics). The $\pm 50\%$ spread in the values of K for the different models of the medium is a measure for the systematic error inherent in the tomographic analysis of jet energy-loss via the nuclear modification function R_{AA}.

However, one may gain predictive power in going to collisions at finite impact parameter **b**. In particular, the ϕ dependence of R_{AA} for non-central collisions constitutes a systematic variation of path-length within a system with fixed overall scale. The average path-length is expected to be smaller for a parton emitted in plane as compared to one emitted out of plane, and hence R_{AA} is expected to be larger at $\phi = 0$ than at $\phi = \pi/2$ with the difference in R_{AA} between these angles increasing with the initial asymmetry (and hence **b**). Using a simple model for the time-evolution of the medium and collective flow effects, it has been shown in [26] that the ϕ dependence of R_{AA} is quite sensitive to the initial gluon density distribution and temporal evolution of the medium.

Utilizing the previously discussed 3-D RFD model [6], we show the p_T dependence of R_{AA} for emission in plane and out of plane at three different impact parameters **b** in the right frame of Fig. 2. As expected, R_{AA} grows for more peripheral collisions as there is less soft matter produced to induce energy loss. Moreover, there is a smooth angular variation of R_{AA} observed, reflecting the underlying medium asymmetry. The difference between in-plane and out of plane emission grows with impact parameter, at **b** = 2.4 fm there is hardly angular variation whereas at 7.5 fm differences are of order 20%.

In summary, we have utilized a 3D hybrid hydro+micro model for a comprehensive and consistent description of soft and hard particle production in ultra-relativistic heavy-ion collisions at RHIC. In the soft sector we have focused on the dynamics of (multi-

)strange baryons, where a clear strangeness dependence of their collision rates and freeze-out is observed. In the hard sector we have studied the radiative energy loss of hard partons in a soft medium in the multiple soft scattering approximation. Our analysis should be seen as the starting point for a comprehensive study of probe-medium interactions treating the hard and soft sector on equal footing.

Acknowledgments

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